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Semi-Infinite Target Design Effects on Terminal Ballistics Performance – Influence of Plate Spacing on Penetrator Energy Partitioning

by Allister Copland, Todd W. Bjerke, and David Weeks

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14. ABSTRACT
The difference in terminal ballistic performance of four semi-infinite target designs fabricated with different amounts of plate spacing was investigated. Three of the target designs were made from 25-mm-thick steel plates stacked together with either 0, 1.5, or 3.0-mm space between each plate. The fourth target design was a single, monolithic block of steel. Each target was impacted with a kinetic-energy penetrator made from tungsten-sintered alloy at an approximate speed of 1600 m/s. Plate spacing was found to result in increased penetration depth. Several energy sink sources are considered to explain the fundamental mechanisms associated with the observed results.

15. SUBJECT TERMS
ballistics, terminal ballistics, penetration mechanics, long rod penetrator, rolled homogeneous armor, monolithic target, laminated target, armor plate spacing

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1. Introduction

In kinetic-energy (KE) penetrator development, improvement, and acceptance testing, penetration capabilities into rolled homogeneous armor (RHA) are routinely used as a benchmark. The thickness of individual RHA plates is nominally limited to a maximum of 150 mm, which is considerably less than the RHA penetration capability of a full-scale KE penetrator. To achieve the thickness needed for testing modern anti-armor long rod penetrators, it is necessary to assemble stacks of individual plates. At the U.S. Army Research Laboratory, the RHA block targets that are routinely used for penetration evaluation are fabricated with several single plates (generally 150 mm thick) that are placed in facial contact and then welded together to form large block targets. Additionally, mild steel straps and angle iron are used to further weld and band the RHA plates together. This fabrication method produces a block target that will not easily separate into individual plates when impacted with a KE penetrator at typical ordinance velocity (1600 m/s). However, this procedure is not universally used. Different configurations are sometimes employed in fabricating RHA block targets that are used for evaluating penetration capabilities. In one case, individual plates are firmly clamped together into a test fixture with the objective of also minimizing any gaps or spaces between plates. Compared to the welding and banding method, individual plate contact in this fixture does not always occur, leaving small gaps between adjacent plates.

Copland and Scheffler[1] reported the results of a series of experiments with small-scale KE penetrators attacking multiplate target arrays. The data in Copland and Scheffler clearly indicate a trend of increase in the depth of penetration as the target transitioned from a monolithic target to targets of increased spacing between plates. This report presents the results from an additional set of experiments that was conducted to verify the apparent trend that emerged from the data obtained from the initial experiments. The partitioning of penetrator energy is also examined to explain the ballistic performance of the different target assembly configurations.

2. Experimental Procedure

A 28-shot experimental series was conducted in Experimental Facility 309A of the Lethal Mechanics Branch. A hemispherical-nose, 65-g, Tungsten alloy X-15C (95% W Teledyne Firth Sterling) rod was packaged with a polypropylux 944A[*] sabot, then push launched from a 50-mm bore diameter experimental laboratory gun. The length of each rod was 142.2 mm, while the diameter was 5.7 mm. Figure 1 illustrates the penetrator, which had a length to diameter ratio (L/D) of 25.

[1]Copland, A.; Scheffler, D. *Influence of Air Gaps on Long Rod Penetrators Attacking Multi-Plate Arrays*; ARL-TR-2906; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2003

*Polyproplux 944A is a trademark of Westlake Plastics, Lenni, PA.

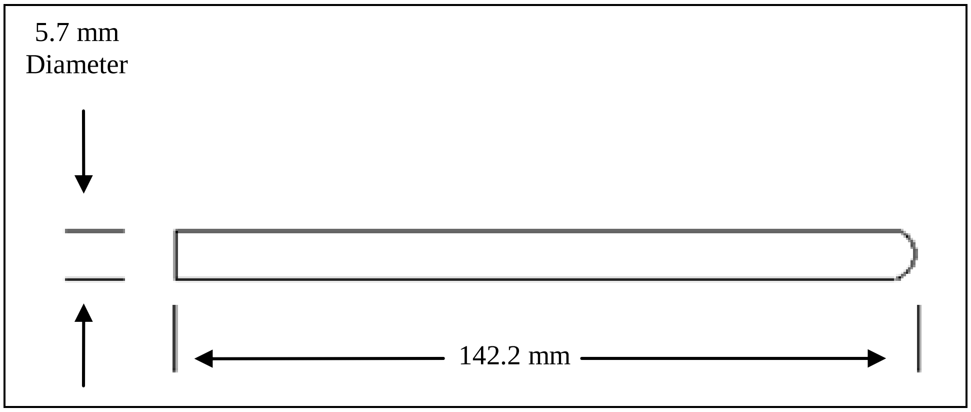

Figure 1. Tungsten alloy X-15C (95% W).

Our objective was to launch each rod at a typical ordinance velocity of 1600 m/s. Four slightly different target configurations were used for this test series. The first was a 150-mm-thick monolithic RHA block, shown in figure 2. The second was made with seven plates each with a thickness of 25 mm that were tightly bonded together with duct tape to eliminate any spacing between plates. The third and fourth types were similarly configured with seven plates each with a thickness of 25 mm; however, a spacing was introduced between the plates. An interplate spacing of 1.5 mm was used for the third target configuration, and a spacing of 3.0 mm was used for the fourth configuration. The spacing was achieved by placing thin strips of sheet metal near the lateral edges of each plate. Figure 3 shows the general configuration used for the second target configuration. The 1.5- and 3.0-mm-spacing values were selected to represent 1/4 and 1/2 of a penetrator diameter.

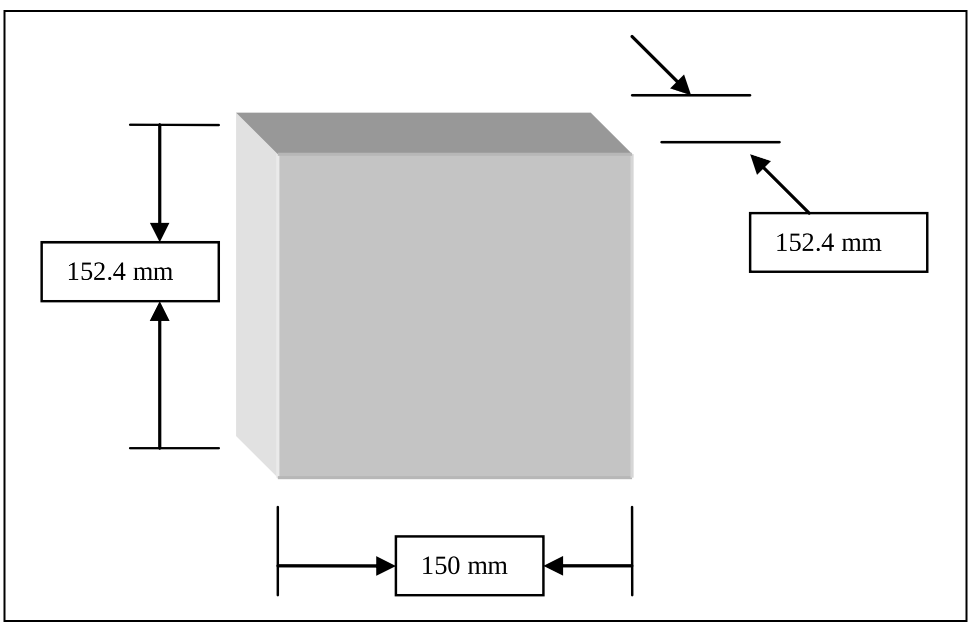

Figure 2. Monolithic RHA block.

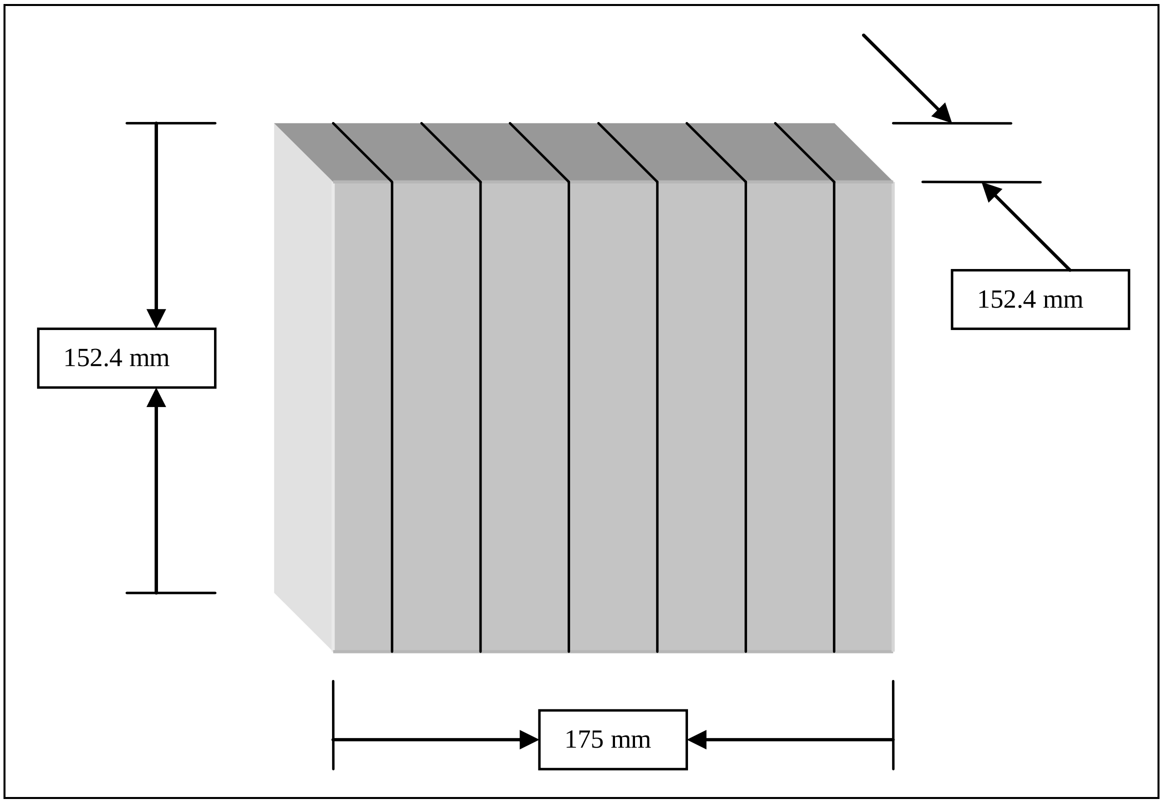

Figure 3. The 25-mm RHA plates in intimate contact.

The experimental procedure consisted of impacting the different target configurations with the KE penetrators and then measuring the depth of penetration into the target. Penetrator impact speed and orientation (pitch and yaw) were determined from a sequence of orthogonal pre-impact x-ray images of the penetrator.

3. Experimental Results

The penetration performance and impact velocity for the experiments are given in table 1. Total yaw is the geometric sum of the penetrator pitch and yaw measured from the orthogonal x-ray images and is calculated by the following equation:

$$Total\,Yaw = \sqrt{(Pitch)^2 + (Yaw)^2}\ . \tag{1}$$

The effect of plate spacing on the penetration depth is shown in figure 4, which includes all experimental data. There is considerable scatter in the penetration data. Excessive penetrator

Table 1. Penetrator impact velocity and penetration performance.

Shot No.	**Target**	**Pitch (°)**	**Yaw (°)**	**Total Yaw**	**Striking Velocity (m/s)**	**Penetration (mm)**
1	150-mm RHA Block	0.25	–0.05	0.254	1574	122.5
2		–0.45	1	1.096	1576	122.0
3		–0.10	0.60	0.608	1599	123.5
4		0.25	1.25	1.274	1571	123.0
5		–1.40	–0.25	1.422	1574	123.0
6		–0.50	–0.05	0.502	1581	125.5
7		–1.75	1.30	2.18	1602	116.0
8		–0.9	–0.05	0.901	1606	127.5
9		–1.30	1.80	2.22	1649	134.0
10		–1.10	0.40	1.17	1621	133.5
11		–0.30	1	1.044	1592	123.5
12		–0.30	0.9	0.948	1595	119.0
13	7 each 25-mm RHA plates	–0.50	0.30	0.583	1607	142.0
14		–0.75	.50	0.901	1628	146.5
15		0.25	1.05	1.079	1595	141.0
16		–0.75	0.05	0.751	1620	143.5
17		0.55	–0.60	0.813	1609	139.0
18	7 each 25-mm RHA plates with 1.5-mm air gap between plates	0.25	0.25	0.353	1598	143.5
19		0.75	–0.35	0.827	1609	144.5
20		0.35	0.90	0.965	1610	145.0
21		–0.05	–0.4	0.403	1597	142.0
22		0.10	0.50	0.509	1620	146.5
23		–1.0	0.25	1.03	1595	141.0
24	7 each 25-mm RHA plates with 3.0-mm air gap between plates	1.45	0.75	1.457	1607	145.0
25		0.25	0.45	0.514	1612	145.5
26		1.10	–0.55	1.229	1608	141.0
27		0.90	–0.40	0.984	1614	147.0
28		–0.25	0.80	0.838	1600	142.0

yaw was shown by Bjerke et al. [2] to reduce penetration performance because the tail of a highly yawed penetrator would impact the crater entrance wall. Given this, only low yaw impact data should be considered for data analysis. The depth of penetration as a function of impact speed for experiments with penetrator yaw less than one degree is shown in figure 5. The scatter in the data is considerably less and shows two clear trends, increased penetration with increased impact speed and increased penetration for the 25-mm-thick plate targets. Additionally, the 25-mm plate array with no spacing yielded less penetration than the spaced plate targets. Differences in penetration between the 1.5- and 3.0-mm-spacing targets could not be detected.

[2]Bjerke, T. W.; Silsby, G. F.; Scheffler, D. R.; Mudd, R. M. Yawed Long Rod Armor Penetration. *International Journal of Impact Engineering* **1992**, *12* (2), 281–292.

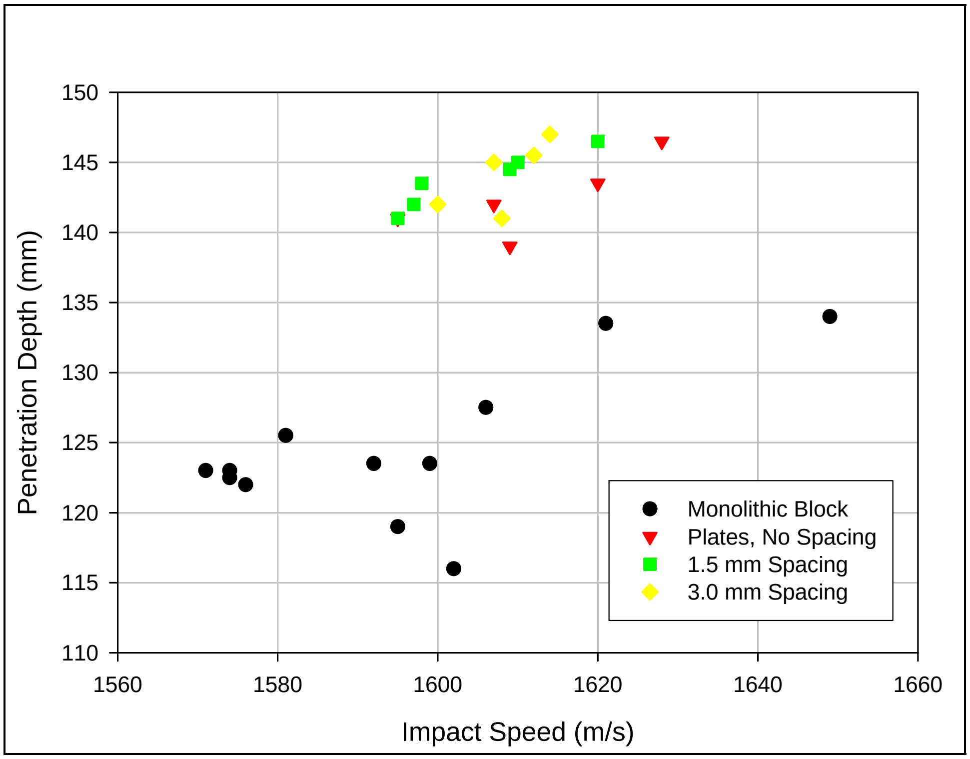

Figure 4. Depth of penetration as a function of impact speed for the four target configurations. All data, including high yaw impacts, are included.

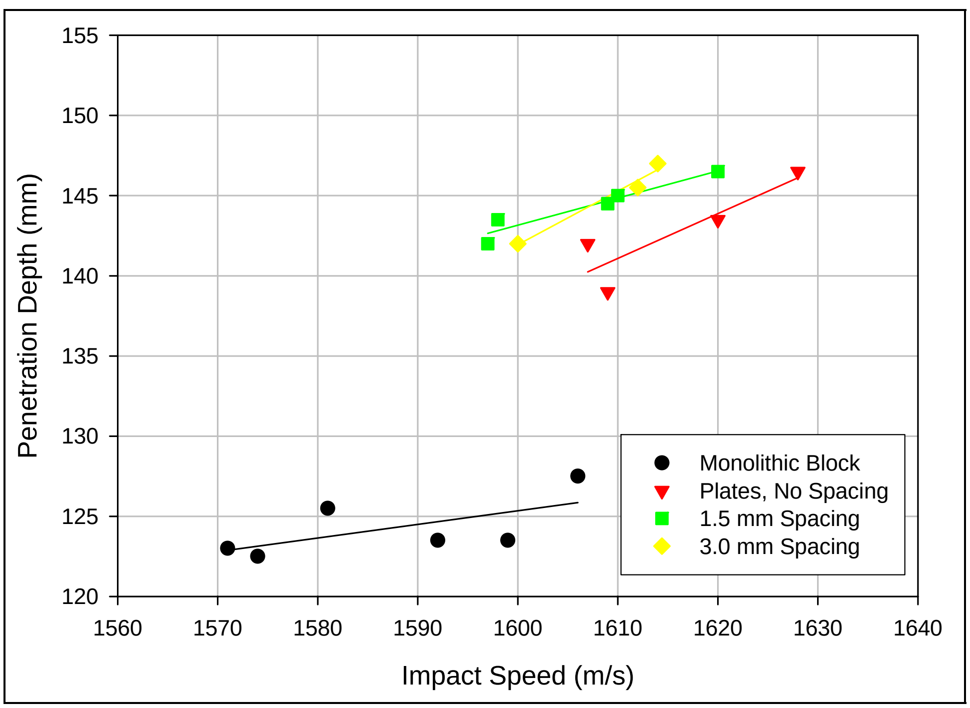

Figure 5. Penetration depth for low impact yaw experiments. A linear interpolation is included for each target type to better indicate the data trends.

4. Analysis and Discussion

The reduced penetration for the monolithic RHA block target is likely due to the increased stress levels the penetrators encounter during penetration compared to the 25-mm-thick plate array targets. During penetration in the plate array targets, material closest to the penetration channel is pushed along the shot line, resulting in a "dishing" deformation on the front and rear surfaces. During the dishing displacement, the individual plate surfaces are free to slip relative to each other. This motion results in a shear stress along the plate surfaces only from sliding friction. For the monolithic target, there are no slip planes every 25 mm along the penetration path so the shear stress that develops is due to the strength of the material and not sliding friction. This results in the shear components of the stress tensor to be considerably higher for the monolithic target, thereby increasing the relative amounts of work and energy per unit length of penetration. A higher penetrator energy consumption results in a decreased overall depth of penetration. To explore this further, several common features on the target plates were measured for comparison.

The plate "dishing" geometry was characterized by the parameters identified in figure 6. In particular, the deformation diameter W, depth h, and penetration channel diameter H were measured for selected 25-mm-thick target plates. The channel diameter was also measured for all of the monolithic targets. The third plate for all of the plate array targets was measured for all three parameters in figure 6.

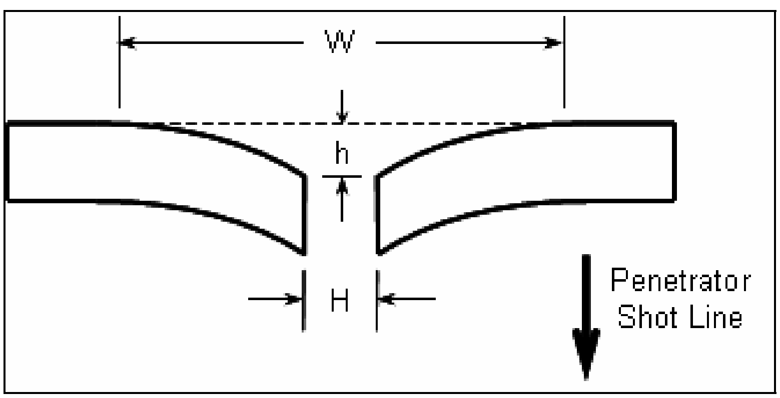

Figure 6. Plate deformation measurements. Figure depicts plate cross section.

The variation in penetration channel diameter, *H*, with impact speed for the different target configurations is shown in figure 7. Only low yaw data was included in the figure. The trend clearly shows the monolithic target to have a smaller channel diameter compared with the other target configurations; however, there was no distinction between the three different 25-mm plate target types. Given the decreased penetration depth and channel diameter for the monolithic target, the results suggest that the additional shearing stresses present during penetration of the

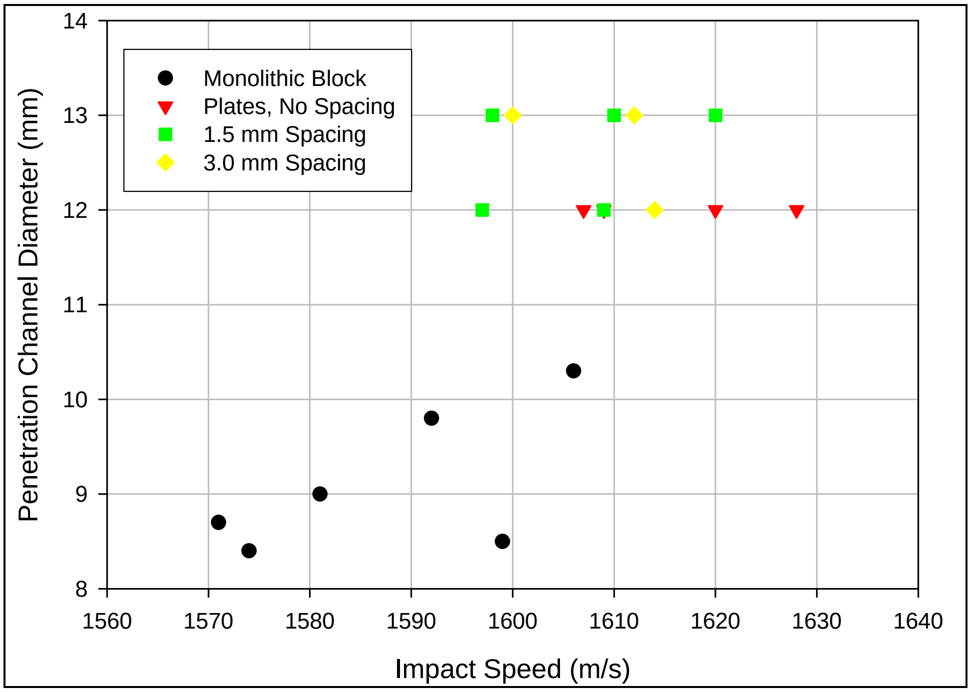

Figure 7. Penetration channel diameter, *H*, shown as a function of impact speed for the four different target configurations.

monolithic target discussed earlier are a significant energy sink Since the channel diameter data did not show a trend that distinguished the three different 25-mm plate configurations, the extent of plate dishing was next examined.

The penetration depth data indicated that the amount of penetrator energy used for axial penetration was less for the 25-mm plate configurations where an air space existed between plates. A possible energy sink that would explain this trend is the amount of plate dishing, as defined in figure 6. The annular region of material that was displaced along the shot line direction is (*W*-*H*) and is plotted as a function of spacing between plates in figure 8. Note that as mentioned earlier, the data is for the third plate in each stack. Although there is scatter in the data, a clear trend of decreasing dishing width with increasing plate spacing is evident. This trend is not entirely intuitive. A possible explanation is that the plates are thick compared to the penetrators diameter, so they do not dish easily when impacted individually (i.e., large plate spacing). It is the added force of the previous plate pushing locally on the plate of interest that adds to the overall dishing width. This is maximized when there is no spacing between plates. The dishing depth, *h*, is shown in figure 9 also as a function of plate spacing. The trend is opposite that of the dishing width trend (i.e., dishing depth increases with increased plate spacing). This is to be expected because spacing changes the boundary condition of the plate, eliminating back surface support.

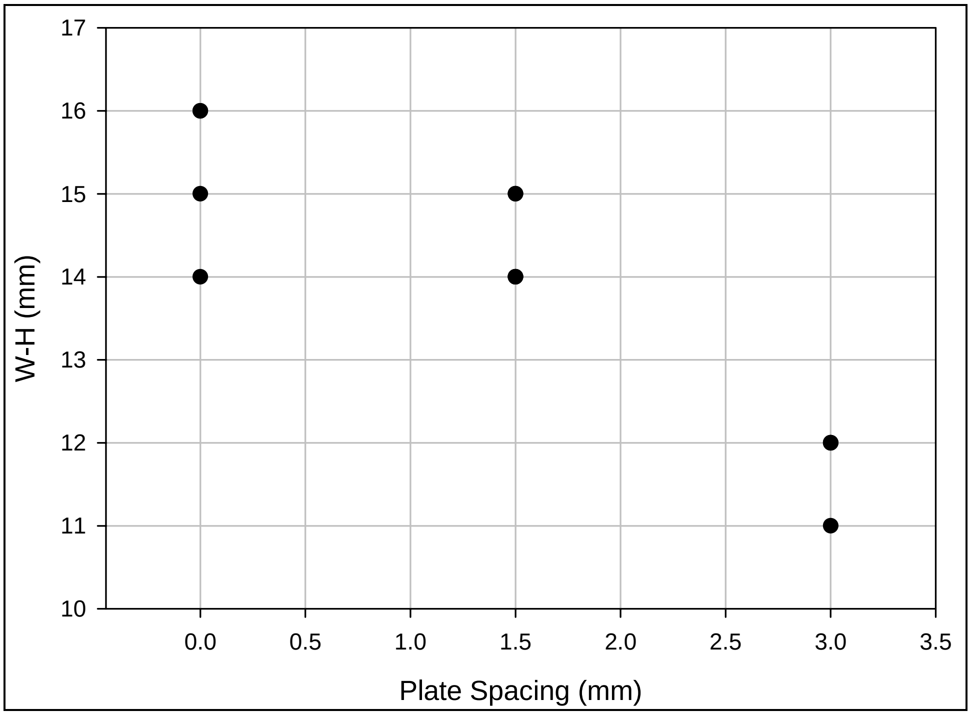

Figure 8. Annular region of dished material in the third plate as a function of plate spacing.

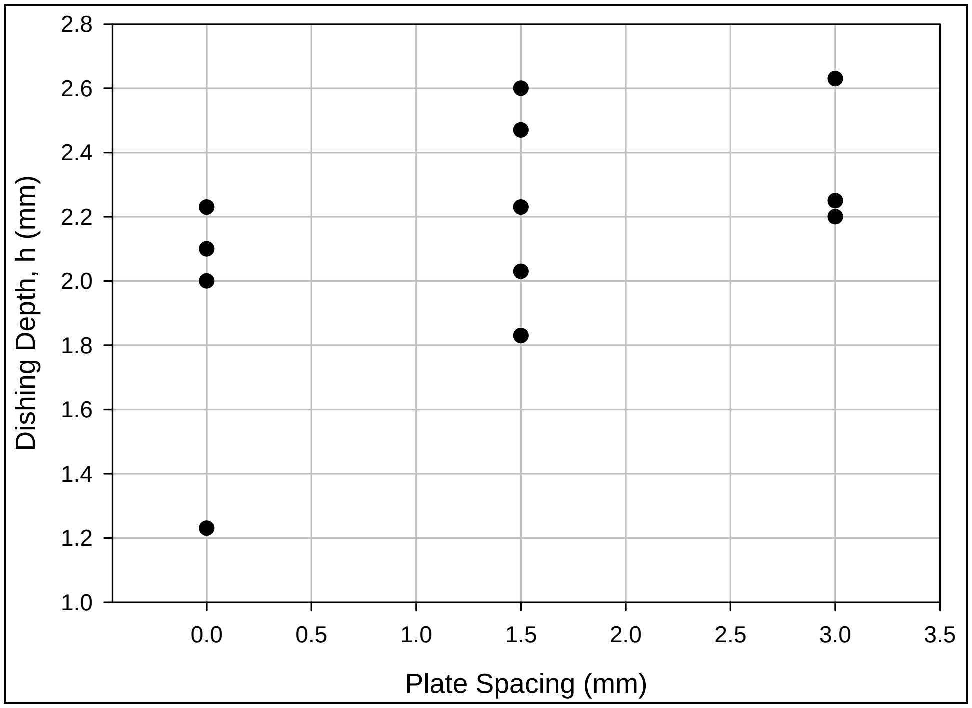

Figure 9. Effect of plate spacing on the dishing depth of third plate.

An attempt was made to combine the annular region metric $h(W\text{-}H)$ with the dishing depth measurement to have an overall dishing "work" measure and to compare this with the measure penetration depths. This was unsuccessful because the impact speed, and hence the kinetic energy, varied enough for each target configuration to prevent a meaningful comparison.

5. Conclusions

The penetration depth of a kinetic energy penetrator into a semi-infinite steel target was found to be influenced by target construction. A solid, monolithic block target resulted in the lowest penetration depth. Using 25-mm-thick steel plates in a stack configuration resulted in increased penetration depth, and the penetration increased when air gaps were introduced between plates. The data suggest that the reduced shear components of the stress tensor resulting from converting a monolithic block to plates of steel result in decreased penetration resistance. This changes the partitioning of energy to enable more efficient penetration. When comparing stacked plate targets with varying amounts of spacing, the case of no spacing resulted in greatest width of plate dishing but also gave the least amount of dishing depth. Spacing between plates decreased dishing width and increased dishing depth. These findings suggest that both penetration depth and localized target plate response is affected by target construction. It is possible to alter the partitioning of penetrator energy into different modes of material deformation depending on target construction details.

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